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Uncertainty Analysis on Fission Product Release Fractions in the SIRIUS Module of the CINEMA Code Based on Correlation Coefficient

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1. Introduction

Korea is currently advancing the development of CINEMA (Code for Integrated Severe Accident Evaluation and Management), a computational framework dedicated to analyzing severe nuclear power plant accidents. This system is designed to replicate accident scenarios in large pressurized water reactors (PWR), encompassing steady-state operations as well as the diverse physical processes occurring under severe accident conditions. To facilitate a detailed and systematic assessment, CINEMA is composed of multiple specialized modules, each focusing on distinct accident phenomena, which collectively enable a comprehensive evaluation.

Severe accident events in CINEMA are classified into in-vessel and ex-vessel phases, depending on whether they occur within the reactor vessel or beyond it. The system comprises four core modules: CSPACE, responsible for modeling core degradation and meltdown behavior; SACAP, which assesses containment-related accident phenomena; SIRIUS, which tracks fission product (FP) behavior; and MASTER, which coordinates interactions among the modules. Each component functions independently, executing simulations based on predefined input sets [1-2].

The SIRIUS module plays a critical role in analyzing the transport and transformation of fission products released from the reactor core into the reactor coolant system (RCS). It models key mechanisms such as aerosol formation, deposition, and movement of fission products through the RCS, steam generator, and containment structures. Since SIRIUS is still undergoing refinement, quantifying its uncertainties is essential to improving its predictive accuracy and reliability.

Given the complexity of severe accident simulations, modeling tools like SIRIUS inherently contain significant uncertainties. These uncertainties arise due to knowledge gaps in accident behavior, variations in scenario parameters, and user-specified model settings. In particular, fission product transport and deposition are influenced by thermohydraulic conditions, aerosol physics, and interactions with containment surfaces, making uncertainty quantification a crucial step in model evaluation.

To address these challenges, this study aims to identify key uncertainty variables that significantly impact aerosol behavior and fission product deposition. A structured methodology is adopted, involving the selection of relevant variables, the generation of diverse input datasets using statistical sampling techniques, and the execution of multiple simulation runs to analyze their effects on SIRIUS predictions.

The core objective of this research is to quantify uncertainties in the SIRIUS module by evaluating the relationships between input uncertainties and the simulation results. As an initial phase of a broader uncertainty assessment framework, this study specifically examines the release fraction of fission products into the reactor coolant system and containment as the Figure of Merit (FOM). The methodology consists of compiling simulation results, applying statistical regression techniques to derive correlation patterns, and assessing how variations in uncertainty parameters influence model outcomes. By delineating the range of uncertainties associated with SIRIUS, this study contributes to refining its predictive performance and enhancing its overall robustness.

2. Methodology

2.1 Target System and Pre-Hydraulic Calculation

The code used in this study consists of four submodules, all belonging to the version CINEMA2.0.2. The detailed versions of each submodule are as follows:

-MASTER2.0.2.118

-SACAP2.0.2.118

-SPACE-SAM_O2p2.0.2.327

-COMPASS.DLL2.0.2.327

-SIRIUS2.0.2.343

In this study, the hypothetical accident scenario for obtaining the generation of thermal-hydraulic data files is a large break loss of coolant accident (LBLOCA) in the optimized pressure reactor1000(OPR1000) without mitigation strategies.

In the process of conducting the uncertainty analysis, the thermal-hydraulic information required for SIRIUS was pre-calculated using other modules that simulate both in-vessel and ex-vessel phenomena, resulting in the generation of thermal-hydraulic data files. These pre-generated thermal-hydraulic data files were then applied to the SIRIUS module to reduce the computational burden associated with the multiple code executions required for the uncertainty analysis. In other words, the thermal-hydraulic information needed for SIRIUS calculations was sourced from these data files, while the uncertainty variables were directly input into the SIRIUS module. By using the thermal-hydraulic data files, the computational time required for the calculations was significantly reduced, and the size of the resulting data was also minimized to a level that is more manageable for data analysis.

The pre-calculation of thermal-hydraulics was performed over a period of 72 hours, and key data such as the pressure behavior of the primary and secondary systems, as well as the core exit temperature, are plotted below.

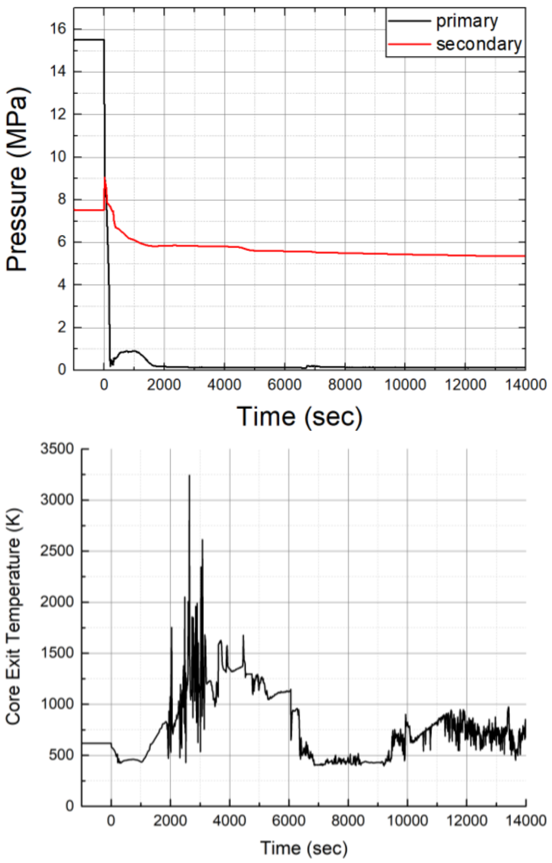

Fig 1. Pressure and CET Behavior in the Reference Scenario

2.2 Uncertainty Variables and Sampling Method

SIRIUS is the module within the CINEMA code responsible for the release, transport, deposition, and removal of fission products (FPs). Therefore, the selected uncertainty variables reflect various phenomena that can influence FP behavior during a severe accident. In SIRIUS, these variables regulate the fraction of FPs existing as aerosols, the characteristics of aerosol particles, and their chemical binding forms, while also determining the heat exchange between FPs and the containment interior. Since certain FPs in aerosol form can pose health risks during severe nuclear accidents, these variables were chosen as key targets for uncertainty analysis [3].

Table 1. Considered Uncertainty Variables

Variables	range
CSF(Collision Shape Factor)	1.0-4.0
SSF(particle Settling Shape Factor)	1.0-4.0
PCE(Particle Capture Efficiency)	0.5-1.0
DCF(Density Correction Factor)	0.5-1.0
RHO(Aerosol Density)	1000-5000
Hy_sol(Hygroscopic Solubility)	1-2
Hy_min(Hygroscopic minimum size)	1.E-07-1.E-06
GAPT(Gap Release Temperature)	1033-1366
Release Model	Discrete

The range of each uncertainty variable was determined through a literature review. Among the variables presented in Table 1[4], CSF and SSF correspond to the uncertainty variables "Agglomeration Shape Factor (GAMMA)" and "Dynamic Shape Factor (CHI)" in the MELCOR code, respectively. PCE represents the probability of an aerosol particle capturing other particles along its path during gravitational settling, while DCF is a correction factor for particle density, assuming a spherical shape for computational convenience.

Additionally, RHO_A represents the density of aerosols, and Hy_sol indicates the ionization rate when hygroscopic materials form aerosols. Since both CsI and CsOH are monovalent ions, their value range is set between 1 and 2. Hy_min refers to the minimum aerosol size for which particle growth due to deliquescence is applied, while GAPT represents the cladding temperature at which gap release begins. The ranges and distributions of these variables were determined based on literature research and their associated physical characteristics [5].

Additionally, the developed code supports various sampling techniques, including Monte Carlo Sampling and Latin Hypercube Sampling (LHS). Given that the input set size in this study is relatively small, the LHS method was selected for its efficiency in generating sufficient samples with a smaller number of input files. Furthermore, the appropriate sample size was determined using Wilks' formula, with a slight margin added, resulting in a total of 153 samples [6]. This series of sampling and preprocessing steps was conducted using the in-house Python code. The in-house code was structured using Python classes, allowing for the application of different ranges and probability density functions to each uncertainty variable.

3. Results

The "horse tail" pattern observed in the code calculation results is illustrated in the figure below. Figure 3 shows the release fraction of FPs released into the containment, while Figure 4 represents the release fraction of FPs released into the RCS.

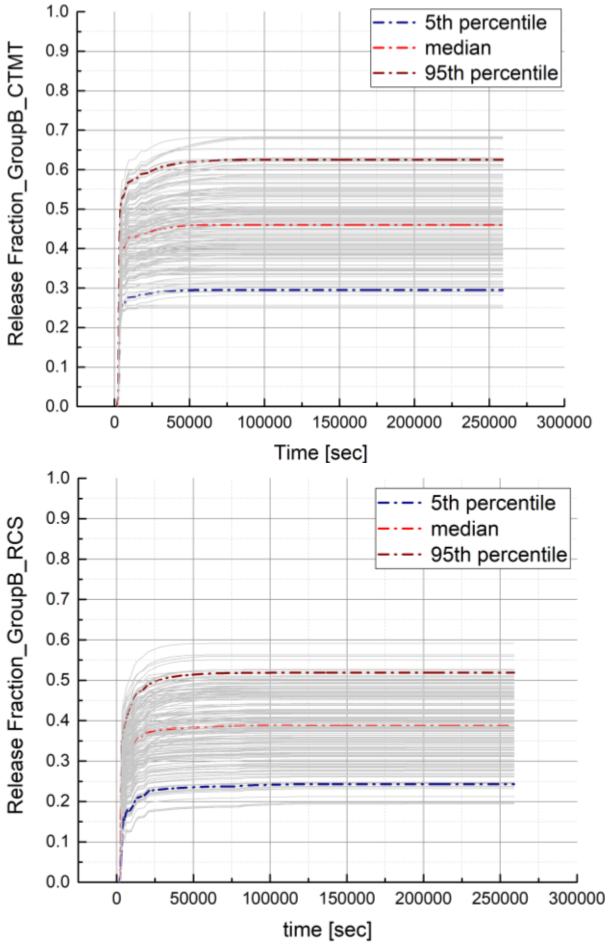

Fig 2. The Hores-tail Plot of FOM

At the beginning of the accident, the correlation with CSF was the most dominant, and this pattern persisted until the end of the event. The Pearson correlation coefficient analysis revealed that, aside from CSF, SSF, and Gap Release Temperature, other variables had a very weak correlation with the Release Fraction, suggesting their minimal impact. The correlation trends of the Release Fraction differed between the RCS and the containment. As illustrated in the data, during the accident, CSF showed a negative correlation with the containment, while SSF exhibited a positive correlation. On the other hand, in the RCS, CSF had a positive correlation during the accident, and SSF displayed a negative correlation.

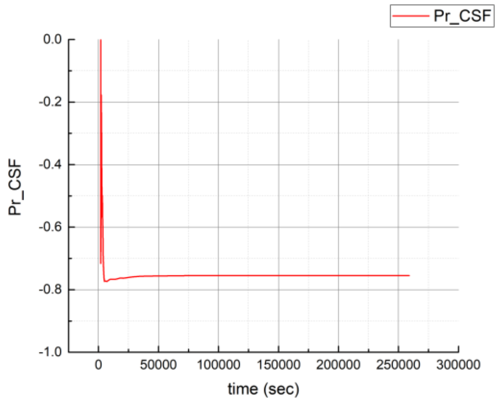

Fig 3. Correlation Coefficient of Group B Release Fraction to CTMT_CSF

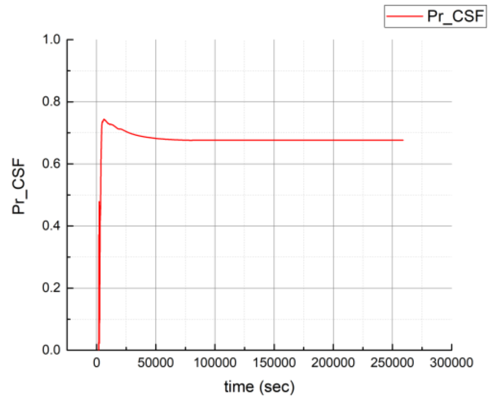

Fig 4. Correlation Coefficient of Group B Release Fraction to RCS_CSF

In severe accident scenarios with a high CSF, the irregular shape of aerosols, as indicated by the elevated CSF, facilitates the growth of aerosol particles and enhances the removal coefficient. This is reflected in the calculations, where, under high CSF conditions, the amount of aerosol removed in the RCS increases before the released FPs can escape into the containment. Consequently, as CSF increases, the release fraction to the CTMT decreases, while the release fraction to the RCS rises. This pattern did not show significant variations across the different FP groups. Based on these findings, it can be inferred that the release of FPs into the environment might decrease under conditions of high CSF.

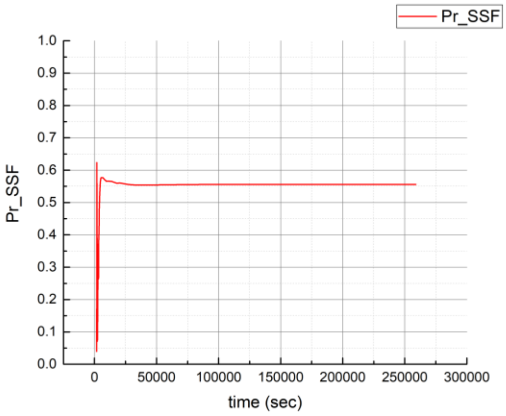

Fig 5. Correlation Coefficient of Group B Release Fraction to CTMT_SSF

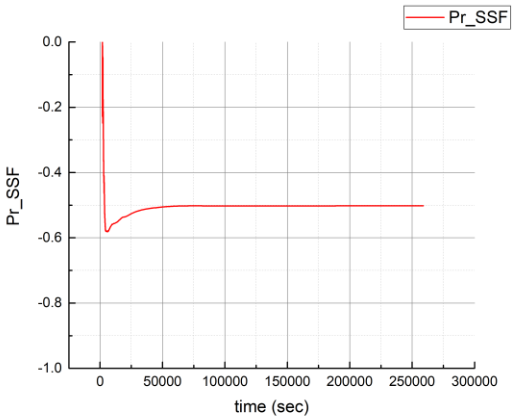

Fig 6. Correlation Coefficient of Group B Release Fraction to RCS_SSF

In contrast, for SSF, in scenarios involving severe accidents and high SSF values, the irregular shape of the aerosols, as represented by the elevated SSF, leads to particles staying suspended longer within the flow, which subsequently lowers the removal coefficient. This effect is evident in the calculations, where, under high SSF conditions, the amount of aerosol removed in the RCS before the particles can escape into the containment is reduced. Consequently, as SSF increases, the release fraction to the CTMT rises, while the release fraction to the RCS decreases. Like the trend observed with CSF, there were no significant differences between FP groups. Based on these observations, it can be concluded that, under high SSF conditions, a greater amount of FPs might be released into the environment.

A comparison of the absolute values of the correlation coefficients for CSF and SSF reveals that, at every time point in the analysis, the correlation coefficient for CSF exceeds that of SSF. This pattern indicates that CSF has a more substantial influence on aerosol behavior than SSF. The rationale behind this result lies in the exponent values for CSF (1.362) and SSF (-1) used in the sedimentation removal coefficient formula applied in the SIRIUS FP behavior simulation module [2].

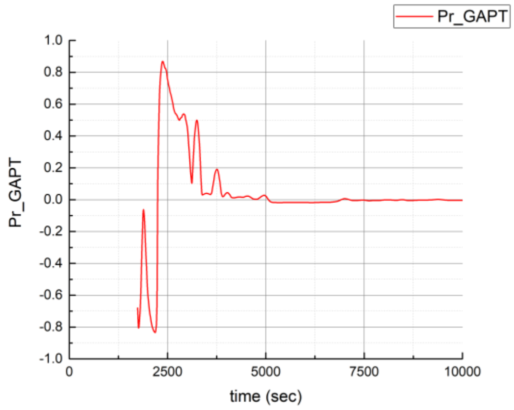

Fig 7. Correlation Coefficient of Group B Release Fraction to CTMT_GAPT

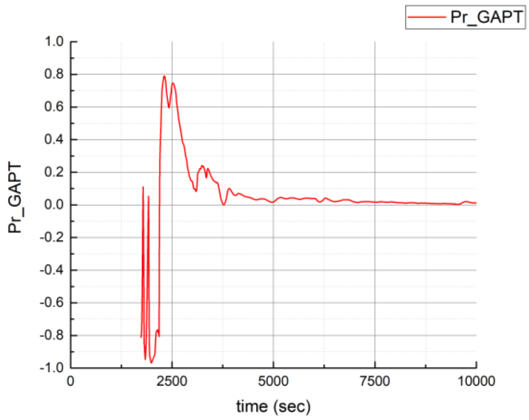

Fig 8. Correlation Coefficient of Group B Release Fraction to RCS_GAPT

Initially, the GAPT showed a negative correlation after the accident but shifted to a positive correlation around 2,500 seconds. This change can be attributed to the fact that a high GAPT delays the release of aerosols, resulting in a slower initial release. However, as the release progresses over time, aerosols are either removed or transported more efficiently in scenarios where FPs are released earlier. In simpler terms, in accident situations with a lower GAPT, aerosols are released and removed more rapidly, which helps explain the observed pattern.

4. Conclusion

This study conducts an uncertainty analysis of the SIRIUS module in CINEMA, focusing on fission product behavior during severe accidents in pressurized light water reactors. Key uncertainty variables, including CSF, SSF, and Gap Release Temperature, were analyzed using Latin Hypercube Sampling (LHS). The Figure of Merit (FOM) was the release fraction of FP. Sampling was performed within defined probability distributions to maintain a 95/95 confidence level, with pre-processing handled by an in-house Python code. The results highlight the impact of uncertainty variables on fission product behavior, improving the reliability of severe accident simulations and nuclear safety assessments.

In severe accident scenarios with high CSF, the irregular shape of aerosols enhances particle growth and increases the removal coefficient. Consequently, more aerosols are removed in the RCS before escaping into the containment, leading to a decrease in the release fraction to the containment and an increase to the RCS. This trend remained consistent across FP groups, suggesting that a high CSF may reduce FP release into the environment.

For SSF, a high value prolongs aerosol suspension, reducing the removal coefficient. As a result, fewer aerosols are removed in the RCS before reaching the containment, increasing the release fraction to the containment and decreasing it to the RCS. Similar to CSF, this trend was consistent across FP groups, indicating that a high SSF may lead to higher FP release into the environment.

The correlation analysis showed that CSF had a stronger influence on aerosol behavior than SSF at all time steps. This is supported by the exponent values in the sedimentation removal coefficient formula used in the SIRIUS FP simulation module, where CSF has a higher exponent (1.362) than SSF (-1).

The GAPT initially exhibited a negative correlation after the accident but shifted to a positive correlation around 2,500 seconds. This is because a high GAPT delays aerosol release, reducing the initial release amount. However, once the release starts, aerosols are removed or transported more quickly in scenarios where FPs were released earlier. In other words, when GAPT is low, aerosols are released and removed faster, explaining the observed trend.

This paper conducted an uncertainty analysis using only the FP behavior-related variables within the SIRIUS module, a unit module in CINEMA. Therefore, it will be necessary to perform a comprehensive uncertainty analysis that also includes the uncertainties of other modules in CINEMA. Such research should incorporate variables that can reflect not only FP behavior but also an overall severe accident scenario. In addition, while this paper analyzed the importance and changes of uncertainty variables through linear regression analysis of the FOM as an analysis of the uncertainty analysis, future studies should apply other analytical methods to examine the distribution and potential uncertainties of the FOM.

ACKNOWLEDGEMENT

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REFERENCES

[1] Korea Hydro & Nuclear Power Co., Ltd., User Manual for CINEMA 2.0, 2022

[2] Korea Hydro & Nuclear Power Co., Ltd., Theory Manual for CINEMA 2.0, 2022.

[3] T. S. Kress, E. C. Beahm, C. F. Weber, and G. W. Parker, "Fission Product Transport Behavior," *Nuclear Technology*, vol. 101, no. 3, pp. 262–269, Mar. 1993, doi: 10.13182/NT93-A34789.

[4] W. Choi, K.-I. Ahn, and S. J. Kim, "Effect of mitigation strategies in the severe accident uncertainty analysis of the OPR1000 short-term station blackout accident," *Nuclear Engineering and Technology*, vol. 54, no. 12, pp. 4534–4550, Dec. 2022, doi: 10.1016/j.net.2022.07.029.

[5] Epstein, Michael, Phillip G. Ellison, and Robert E. Henry., "Correlation of aerosol sedimentation.," *Journal of colloid and interface science*, vol. 113, no. 2, pp. 342–355, 1986.

[6] N. W. Porter, "Wilks' formula applied to computational tools: A practical discussion and verification," *Annals of Nuclear Energy*, vol. 133, pp. 129–137, Nov. 2019, doi: 10.1016/j.anucene.2019.05.012.